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Contract No. NASw - 702

THIRD QUARTERLY STATUS REPORT

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WASHINGTON 25, D.C.

January 30, 1964

A D V A N C E D   K I N E T I C S, I N C.

THIRD QUARTERLY REPORT

I) RESEARCH ACTIVITY

During this third quarter of contractual operation the major achievement has been the completed installation of a new and larger vacuum chamber. The enlarged chamber is now a total of 135 cm long. The glass cylinder used for viewing the interaction is 105 cm long and 30 cm in diameter. It is hoped that this chamber will first of all eliminate any objections to the existence of wall effects in the experiment, and it should facilitate the study of the "down-stream" plasma, that is, the "dark side" of the magnetosphere.

To accompany the expansion of the vacuum chamber, several modifications in the auxiliary apparatus were made. The dipole was reconstructed in order to locate the dipole field some 40 cm from the end of the glass portion of the vacuum chamber, a distance considered sufficient for observation of the plasma structure in the tail of the magnetosphere. Another feature that has been added is a liquid nitrogen trap which is placed inside the vacuum for the purpose of cryogenic pumping. This device has made it unnecessary to make major alteration in the pumping system as a vacuum of 2×10^{-6} is presently attained with the addition of this cryogenic structure. Another major improvement that has been made is the location of a mirror above the glass vacuum chamber to make possible simultaneous image converter photography of both the equatorial and polar view of the interaction. The appropriate optical modifications have been made on the image converter camera to permit photography of both the mirrored equatorial plane and the midnight meridional plane (solar meridional plane). This step facilitates three-dimensional analysis of the observed geomagnetic cavity.

Further image converter pictures of the interaction have been taken. The image converter photographs, as reported in the previous quarterly report, reveal a polar phenomenon that looks as if plasma has entered the cavity at the point where the theoretical models of the cavity indicate the neutral points above the poles to be located. Mention was also made of the fact that as the angle between equatorial plane and the axis of the plasma gun (the direction of plasma flow) was increased, the polar phenomenon was found to disappear for angles greater than about 9° as will be explained in the accompanying text. It was suspected that the disappearance of the polar phenomenon may be due more to the structure of trapped magnetic field in the plasma (even though this field is only a few gauss) than to the angle of injection. Thus, a three-dimensional magnetic probe, i.e., capable of measuring the three components of the magnetic field simultaneously, was designed and constructed. This probe has been used to map out the radial distribution and shape of the magnetic field that is trapped in the plasma during the acceleration process. The structure is found to be very complex. A metallic conductor designed to allow the trapped magnetic field to be "filtered out" has been installed between the plasma gun and the dipole. However, the concomitant decrease in the velocity of the plasma stream has decreased the usefulness of this approach, pending further improvements.

As reported in the Second Quarterly Report, a system of ten single Langmuir probes was installed and placed in the region of the plasma-field interaction with the purpose of making quantitative observations on the location and shape of the cavity boundary, and to compare these with theoretical predictions.

Measurements of the cavity boundary location on the axis of the tube (earth-sun line) have already been reported. In this quarter, sufficient data was taken with the bank of Langmuir probes, to present in the attached report the accurate shape of the cavity in the equatorial plane, on the day-side. Quantitative observations on the night side, aside from image converter camera pictures, so far have not been possible. Further efforts are being made to study this controversial region in more detail.

The question of crowbarring the magnetic field has been raised. To be able to study somewhat longer range interaction, instabilities and injection mechanisms, slower varying magnetic fields are necessary.

The difficulty with crowbarring is the very low inductance of the present dipole circuit. Calculations were made to find the necessary criteria for efficient crowbarring. These are presented in the accompanying report also.

It was found that for effective crowbarring the inductance of the dipole coil (with its feeder circuit) should be at least twenty times the inductance of the crowbarring circuit. Since at present with our one turn coil this is not possible a multiturn coil has been designed and is presently under construction.

II) ACTIVITIES PLANNED FOR NEXT QUARTER

Using the new large vacuum chamber the interaction will be further diagnosed using all three methods: magnetic and Langmuir probes and image converter camera pictures. Emphasis will be placed on viewing the night side and the polar region.

If crowbarring is successful, longer time study of the cavity boundary and its stability will be possible. Attempts will also be made to produce a more uniform plasma, since the presence of a radial density gradient makes comparison with theoretical prediction more susceptible to errors.

III) SCIENTIFIC REPORTS AND PUBLICATIONS

A paper on "Experimental Observations of Plasma Flow Against a Three-Dimensional Magnetic Dipole," by R. S. Lowder, S. W. Lee, and R. W. Waniek, has been presented at the Plasma Physics Meeting of the American Physical Society, San Diego, November, 1963.

A paper entitled "A Megampere, High Vacuum, Low Inductance Current Feedthrough" has been submitted to NASA Headquarters for release to publish. The paper will be submitted to the Review of Scientific Instruments for publication. The same paper has been forwarded to the NASA Patent Office as a disclosure of New Technology developed under this contract.

A paper on "Experimental Studies of a Hydrogen Plasma Flow Against a Three-Dimensional Magnetic Dipole" is being prepared for publication.

A further paper on "A Plasma Tunnel for Investigations of High Speed Flows" is presently under preparation.

Reprints of the paper entitled "Approximation of an Ideal Dipole with a Solenoid," by Clark Benson, have been distributed to NASA Headquarters and to interested parties.

IV) PERSONNEL

The following personnel were engaged in work on this contract during this quarter:

A. N. Dienes
H. J. Gilsdorf
S. W. Lee
R. S. Lowder
R. W. Waniek

SCIENTIFIC REPORT

A) MEASUREMENT OF THE CAVITY BOUNDARY

The general experimental apparatus is the same as Fig. 1, Second Quarterly Report (October 15, 1963). The arrangement of the ten Langmuir probes is shown on Fig. 1 (this report). Each probe consists of a single silver plated steel wire of length 1/8", connected to the center conductor of a Microdot coaxial cable. The cable is insulated from the plasma by a glass tube which also serves as rigid support for the probe. The probes are biased negatively and draw saturation ion current. Each prohe has its own circuit and is completely independent of the others. There is no noticeable crosstalk observed. The area of each probe is very closely the same but its value has not been calculated since in this case the probes served only 1) as indicators of the arrival of the plasma boundary, 2) to measure relative density gradient radially across the tube.

In Fig. 2 we show a sample of probe signals which were used, along with others, to calculate the position of the boundary at $t = 17.5$ μsec after gun breakdown, when the magnetic field has decayed to approximately 0.65 times its peak value. Fig. 2 (1) is the signal of probe F-5 (on the axis). The arrival of the plasma boundary is indicated by the disappearance of the trace. From this we calculate the velocity of the boundary $v_z\ (\rho = 0) = -\frac{11}{16}/3 = -\frac{11}{48}$ in/μsec

[Note: In the following conventional cylindrical coordinate system will be assumed, with origin at the dipole and z axis along the axis of the tube, direction toward the gun positive. The symbol r or R will mean radial distance in a spherical coordinate system also centered on the dipole.]

Fig. 2 (2) is probe F-5 and B-3. At $t = 17.5$ μsec the boundary appears simultaneously at both, hence we have the following 2 points for the boundary

$$P_1\ (z = 1.4"\ ;\ \rho_1 = 2") \qquad \text{and} \qquad P_2\ (z_2 = 2.1;\ \rho_2 = 0)$$

To get a third point (at $\rho = 1$): from Fig. 2 (3) the boundary arrives to F-4 approximately 1 μsec before it arrives to F-5.

From Fig. 1 (4) and (5) $v_z\ (\rho = 1) \approx -\frac{11}{16}/4 = -\frac{11}{64}$ in/μsec = -0.17 in/μsec.

$$\therefore\ z_3 = z_2 - v_z\ (\rho = 1) \times \Delta t = 2.1 - 0.17 = 1.93 \text{ inches}$$

Thus $P_3\ (z_3 = 1.93;\ \rho_3 = 1)$

Another series of shots give very closely the same result.

These points, and another set corresponding to $t = 15$ μsec (magnetic field at peak) which is determined the same way are plotted on Fig. 3. They are located to a very good accuracy on a circle with center on the z axis, but not at the dipole. There is a crosscheck that can be made here. If the distance of the boundary on the z axis at $t = 15$ and 17.5 μsec is given by d_A and d_B respectively, then

$$(d_B/d_A)^3 \equiv m\ (t = 17.5)\ /\ m\ (t = 15) = m_B/m_A$$

where m is the strength of the dipole at that instant. From Fig. 1 (6)

$$m_A = \text{const.} \times 1.0 = C$$

$$m_B = \qquad\qquad = 0.65C$$

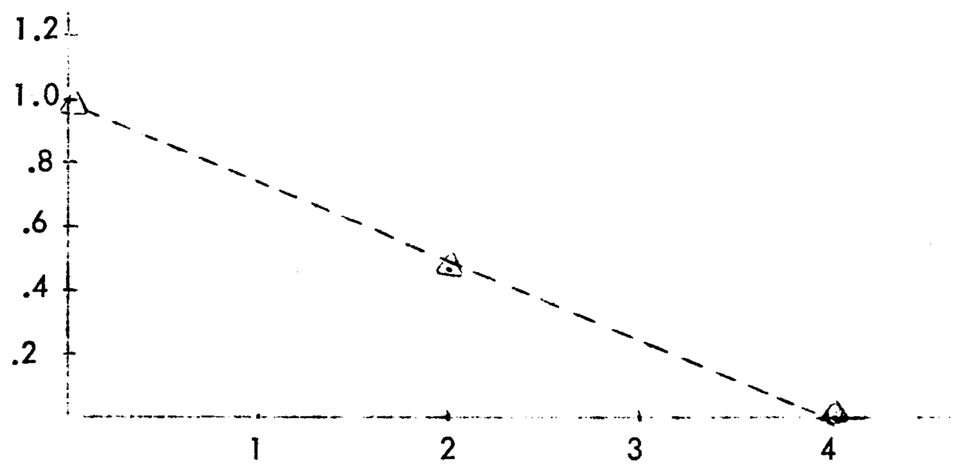
$$m_B/m_A = 0.65$$

$$(d_B/d_A)^3 = (2.1/2.4)^3 = 0.67$$

Thus the agreement is seen to be very good and we can accept the profile plotted as quite accurate. Comparison of the boundary thus obtained with that shown by image converter camera pictures also shows excellent agreement.

According to theoretical predictions (e.g. Beard, Ferraro) the shape of the cavity on the daylight side is approximately spherical in shape. The cross sections in the equatorial plane of Beard's approximate surface is shown dotted on Fig. 3, for the same location of boundary at the axis. The measured surface section is seen to differ by having a somewhat larger radius of curvature. The difference is larger in the earlier boundary.

In the following, an attempt is made to modify the theoretical curvature of Beard to account for the non-uniform plasma density. The density is maximum on the axis and decreases to a lower value near the walls of the tube. The measured radial variation of plasma density is shown below. We do not know yet the exact shape of the curve, but as this is only an approximation, the linear variation shown will be used. See the following sketch.



According to the theory $r_o^3 = m \ (8\pi p)^{-1/2}$, where r_o is the nearest point of the boundary surface to the dipole.

Thus since $p \propto n$, $r_o \propto n^{-1/6}$

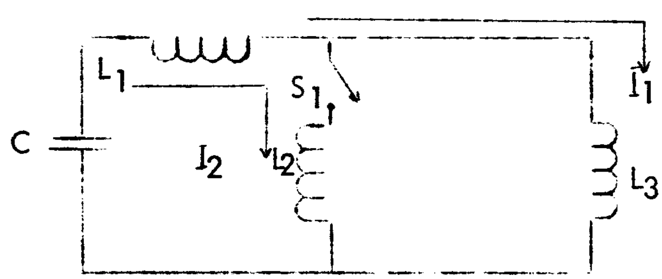
On Fig. 4 a series of theoretical surfaces are drawn for decreasing n and for a given value of ρ the point on the proper surface is located.

At $\rho = 1$ in.	$n = 0.75\,n_o$	$r_o = (1/0.75)^{1/6} R_o = 1.05 R_o$
$\rho = 2$ in.	$n = 0.5\,n_o$	$r_o = (2)^{1/6} R_o = 1.12 R_o$
$\rho = 2.75$ in.	$n = 0.3\,n_o$	$r_o = (1/0.3)^{1/6} R_o = 1.22 R_o$

Where R_o is the location of the boundary on the axis at any given time. Theoretical surfaces wiih these r_o are shown and the corresponding three points plotted. The resultant curve with the same R_o as the $t = 15$ μsec boundary is shown in dark. The dotted line is the experimental curve. We see that up to $\rho = 3"$, i.e., up to an angle of 70° from the earth-sun line, the theoretical and experimental curves agree to within 10%. With the present expreimental accuracy this agreement is considered satisfactory.

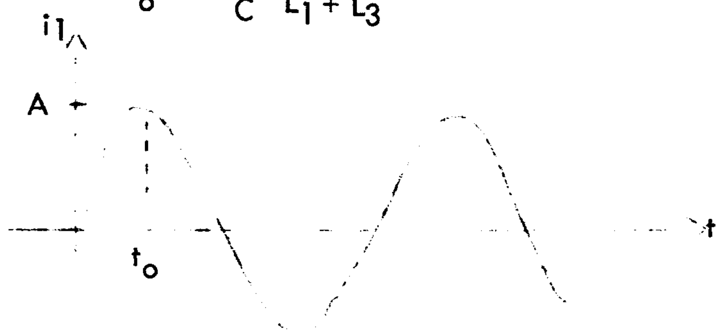
B) ON THE PROBLEM OF CROWBARRING A LOW INDUCTANCE CIRCUIT

In most applications of crowbarring, the load inductance is quite high compared to the inductance of the crowbarring circuit. In such case, the only problem is to keep resistance to a minimum for slowest decay of the crowbarred magnetic field. In this experiment however, the inductance of the dipole coil is very low (approximately 30 nanohenries). Since the crowbarring circuit will almost certainly have an inductance of the same order of magnitude, the problem arises, how much larger must the load inductance be so that the resulting ripple in the field is negligible? A somewhat simplified analysis follows in which all resistances have been omitted. The circuit is shown below. L_1 is the inherent inductance of the capacitor bank which is of the same order of magnitude as L_2, L_3.



If the crowbar is not operating, the current in the coil is $i = A \sin \omega_o t$

where $\omega_o^2 = \frac{1}{C} \frac{1}{L_1 + L_3}$



If the crowbar switch is closed at $t = t_o$ the following equations hold.

$$I_1 \left(\frac{1}{Cs} + L_1 s + L_3 s \right) + I_2 \left(\frac{1}{Cs} + L_1 s \right) - i_1 (0^-)(L_1 + L_3) = 0 \qquad (1)$$

$$I_1 \left(\frac{1}{Cs} + L_1 s \right) + I_2 \left(\frac{1}{Cs} + L_1 s + L_2 s \right) - i_1 (0^-) L_1 \qquad (2)$$

(Note: To facilitate calculations, the origin has been shifted to $t = t_o$)

Eliminating I_2 between these equations:

$$I_2 = i_1 (0^+) \frac{L_1 Cs}{1 + (L_1 + L_2) Cs^2} - I_1 \frac{1 + L_1 Cs^2}{1 + (L_1 + L_2) Cs^2}$$

Substituting:

$$I_1 \left\{ \frac{[1 + (L_1 + L_3) Cs^2] [1 + (L_1 + L_2) Cs^2] - (1 + L_1 Cs^2)^2}{[1 + (L_1 + L_2) Cs^2] Cs} \right\} =$$

$$i (0^+) \left\{ L_1 + L_3 - \frac{L_1 (1 + L_1 Cs^2)}{1 + (L_1 + L_2) Cs^2} \right\}$$

Let $i\,(0^+) = 1$

$$I_1(s)\ \frac{(1 + L_1 C s^2)\,(L_2 + L_3)\,C s^2 + L_2 L_3 C^2 s^4}{[1 + (L_1 + L_2) C s^2]\,C s} = L_1 + L_3 - \frac{L_1(1 + L_1 C s^2)}{1 + (L_1 + L_2) C s^2} \qquad (3)$$

From which we get by breaking up into elementary Laplace transforms

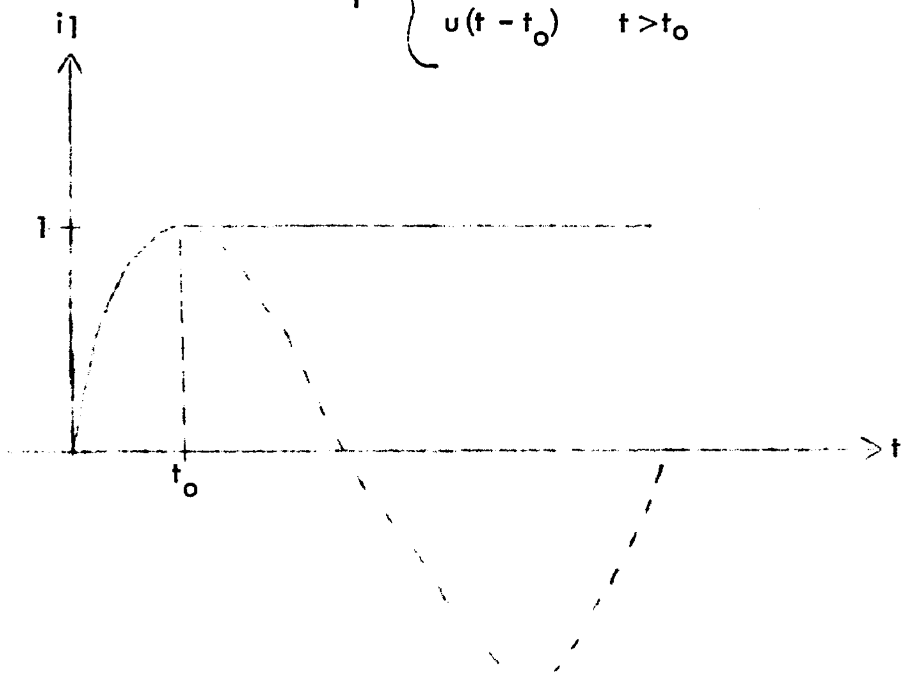
$$I_1(s) = \frac{k}{s} + (1 - k)\,\frac{s}{s^2 + b^2} \qquad (4)$$

where $k = [L_3 / (L_2 + L_3)]^2$

This result shows that if $L2 = 0$ we have perfect crowbarring, i.e., $k = 1$ and $I_1(s) = 1/s$. The current from $t > t_o$ is a step function of amplitude $i_1(t_o^-)$.

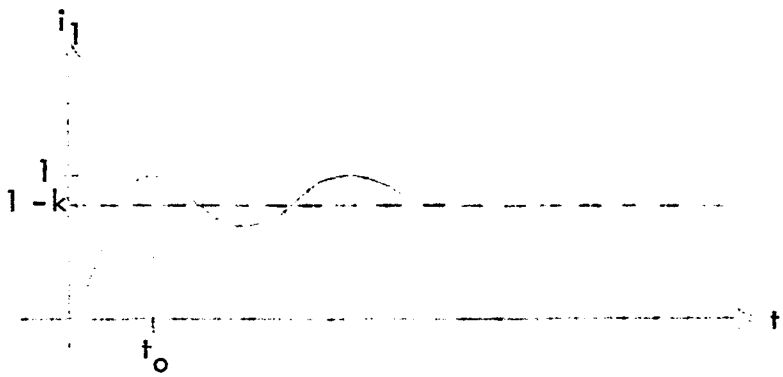
Thus the total load current is

$$i_1 = \begin{cases} \sin \omega_o t & t < t_o \\ u(t - t_o) & t > t_o \end{cases} \qquad (5)$$



If however $L_2 \neq 0$

$$i_1 = \begin{cases} \sin \omega_o t, & t < t_o \\ k\ u(t - t_o) + (1 - k) \cos \omega_o t, & t > t_o \end{cases} \tag{6}$$



The frequency of ringing after crowbarring is $\omega_c = b$ where

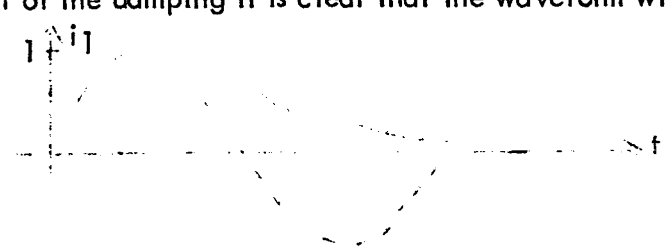
$$\omega_c^2 = \frac{1}{C} \frac{L_2 + L_3}{L_1 L_2 + L_2 L_3 + L_1 L_3} = \frac{1}{C} \frac{1}{L_1 + \frac{L_2 L_3}{L_2 + L_3}}$$

The ratio of the new ringing amplitude to the old is given by

$$(1 - k)/1 = 1 - k = 1 - [L_3/(L_2 + L_3)]^2$$

$\therefore$ For example if $L_2 = L_3/5$ $\quad L_3/(L_2 + L_3) = 5/6 \quad \therefore 1 - k = 1 - \frac{25}{36} \doteq 0.3$

i.e., the ratio of the new ringing amplitude to the old is about 30%. If we take account of the damping it is clear that the waveform will be of the shape:



We see that for effective crowbarring $L_2 \ll L_3$

If $L_2 \approx L_3/20 \qquad 1 - k \approx 9\%$.

L_2, L_3 have been experimentally measured to be approximately 20 and 30 nH respectively. Very careful engineering of the crowbarring circuit could reduce L_2 to perhaps half this value. In this case $1 - k = 1 - (30/40)^2 = 0.45$ and crowbarring is completely ineffective. Thus we conclude that a multiturn coil with much higher inductance for L_3 is necessary.

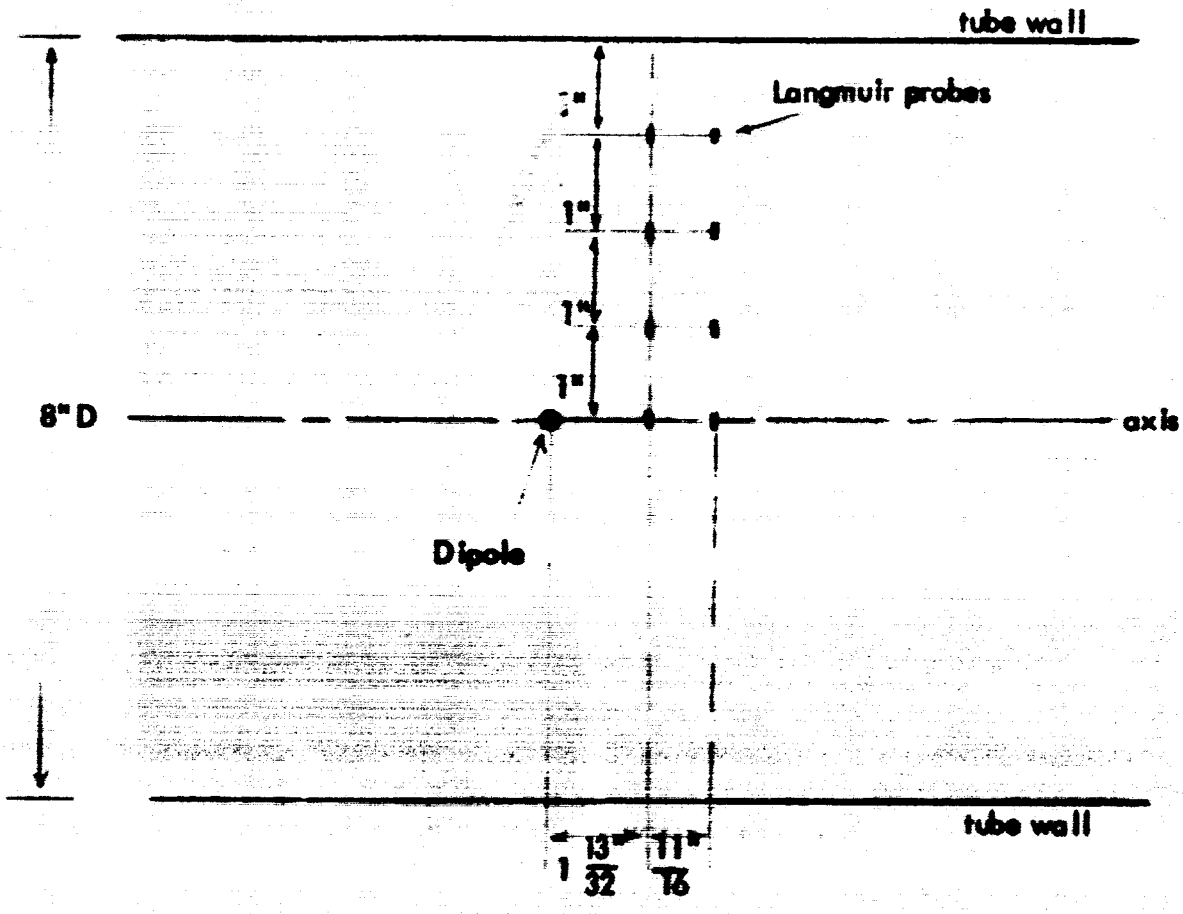


Fig. 1: Arrangement of Probes

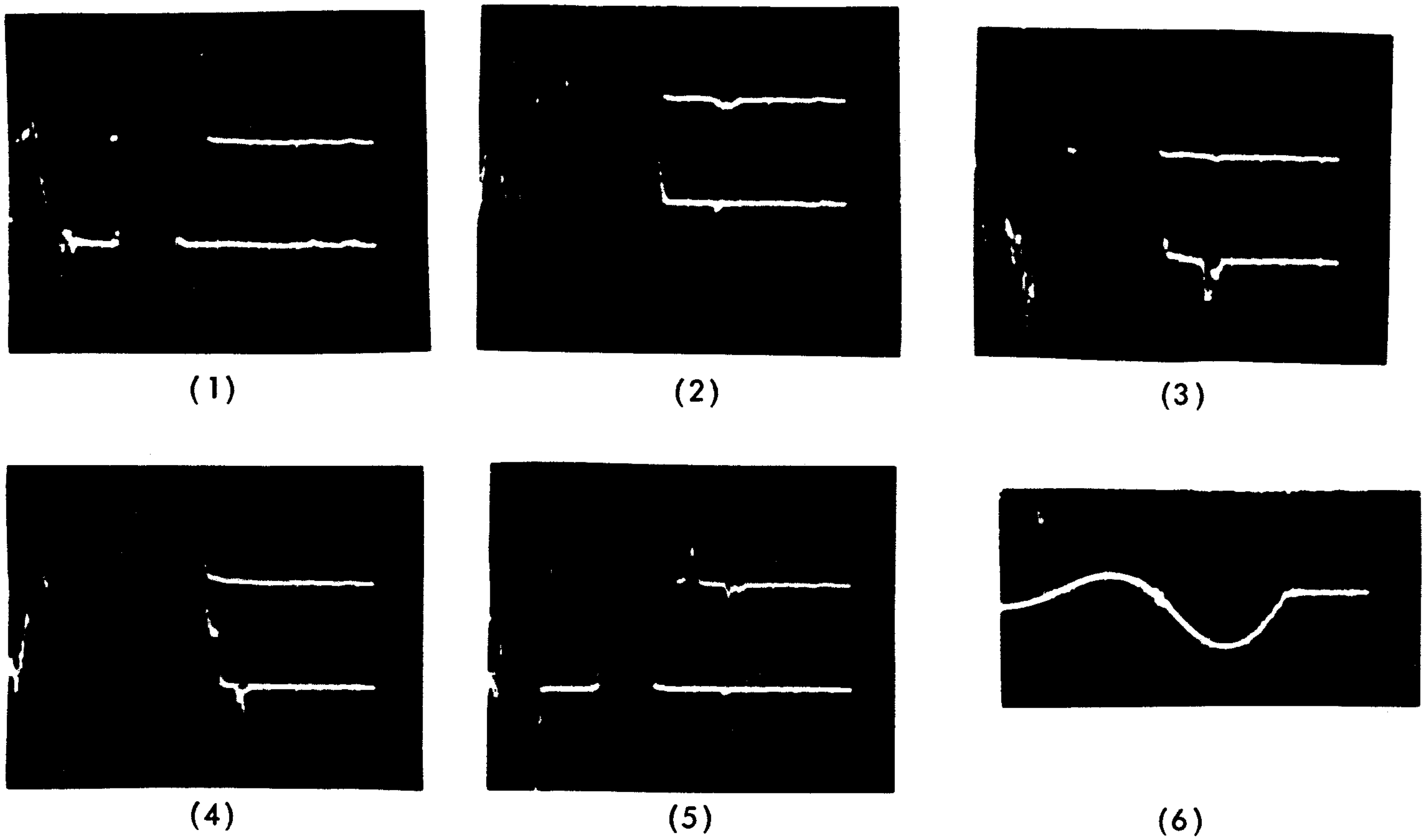


Fig. 2: Langmuir probe observations of the cavity boundary, taken with the system shown on Fig. 1. Trace sweeps right to left at 5 μsec/cm. The upper trace on each is probe F-5, the lower is another probe.

(1) Probe B-5 (2) Probe B-3 (3) Probe F-4

(4) Probe F-4 (5) Probe B-4 (6) Magnetic Field

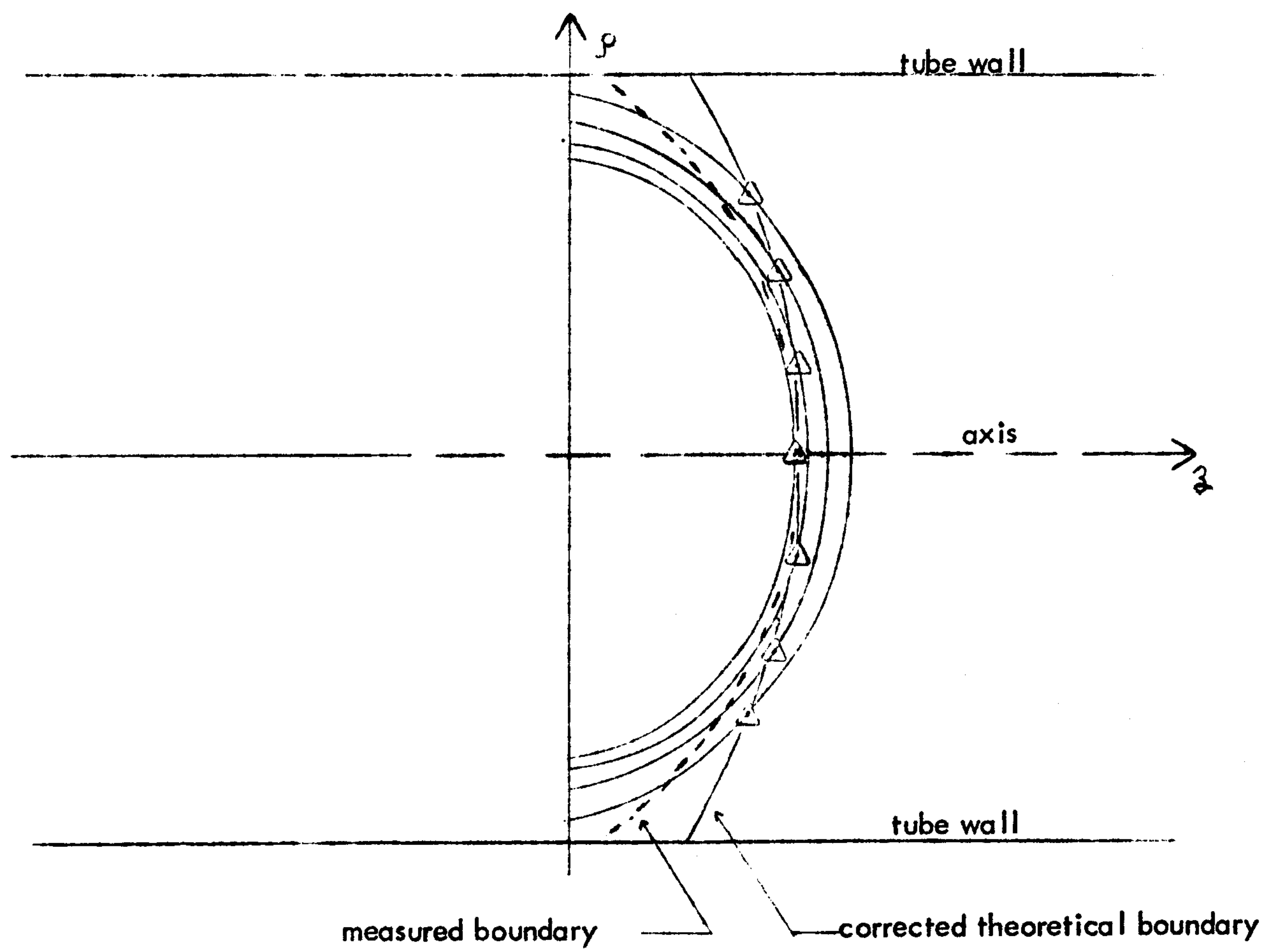


Fig. 4: Comparison of measured cavity profile with the theoretical curve, corrected for radial density gradient of the plasma

A MEGAMPERE, HIGH VACUUM, LOW INDUCTANCE CURRENT FEEDTHROUGH*

R. S. Lowder and R. W. Waniek
Advanced Kinetics, Inc., Costa Mesa, California

INTRODUCTION

In plasma physics experiments the need sometimes arises to feed a high current pulse from a capacitor bank into a low inductance load located inside a vacuum chamber. In this particular case, during the study of the interaction of a plasma flow against a magnetic dipole[1], a current pulse of 0.4MA was necessary to energize a single turn coil[2] simulating the geomagnetic field in accordance with a selected scale factor.

The problems encountered involve the mechanical stresses on the conductors due to the high current, the need for retaining absolute vacuum tightness in spite of the mechanical shock occurring during current passage, and finally the requirement of keeping the inductance of the feedthrough as low as possible to achieve efficient energy transfer into the load.

The solution arrived at after a series of experiments is presented in the following and the usefulness of this configuration is borne out by the trouble-free, long-term operation achieved with this device.

*Research supported by the National Aeronautics and Space Administration, Washington, D.C.

GENERAL CONSIDERATIONS

After considering several alternate configurations, the geometry with cylindrical symmetry was found to possess all the desirable features needed for the high current feedthrough.

A coaxial line exhibits an inductance per unit length of

$$L = 2 \times 10^{-7} \left[\ln (a_2/a_1) + \frac{1}{4\pi} \sqrt{\frac{10^7}{f\sigma}} \; \frac{a_1 + a_2}{a_1 a_2} \right] \tag{1}$$

where a_1 and a_2 are the radii of the inside and outside conductor, f the frequency and σ the conductivity of the metal used.

For a typical load inductance of 20 nH, a maximum inductance of only a few nanohenries can be allowed for the feedthrough from efficiency considerations. Including effects due tothe skin depth of the current in the conductor, such an inductance can be realized in practice by a cylinder of 1.450" diameter separated from its coaxial return path by a 0.020" thick insulator. A maximum length of 12" can be used in such case, resulting in an inductance of 3 nH, which satisfies the efficiency requirements.

The force between the two cylinders during current passage is due to the pressure generated by the azimuthal magnetic field B_θ and may be calculated from

$$\Phi = LI = B_\theta l (a_2 - a_1 + 2\delta) \tag{2}$$

$$P_m = B_\theta^2 / 2\mu_o = \frac{1}{2\mu_o} \left[\frac{L}{l} \cdot \frac{I}{(a_2 - a_1 + 2\delta} \right]^2 \tag{3}$$

where A is the area of the ring between outer and inner conductor including one skin depth at each boundary, L/l is the inductance per unit length. For an assumed design value of the current of 10^6 A, the B_θ field will amount to 90kOe and the corresponding magnetic pressure will rise transiently to 324 atm or roughly 4,800 psi. If hard brass is selected as the material for the outer conductor (return path) a minimum thickness of about 0.5" would be necessary to avoid expansive forming of the tubing. This figure is determined from the magnetic yield strength [(2)] of brass which is between 50 and 70 kpsi and from the hoop stresses characteristic of the configuration, as obtainable from the equation

$$w_{min} = R\,(B_\theta^2 \,/\, B_{crit}^2) \qquad (4)$$

where w_{min} is the minimum thickness of the outer conductor, R its radius, B_{crit} is the magnetic yield point of the material used. A further point to be considered is the minimization of resistive losses in the coaxial line by using copper for the central conductor. The unit length resistance of the feedthrough is then

$$R = \frac{1}{\sqrt{4\pi}} \sqrt{\frac{f\mu_o}{\sigma}} \left(\frac{a_1 + a_2}{a_1 a_2}\right) \qquad (5)$$

which for the parameters used before amounts to 10^{-5} Ohms/meter.

DESCRIPTION AND OPERATION OF THE FEEDTHROUGH

The feedthrough design is shown in Figure 1. The pulsed current from a 18 kilojoules capacitor bank is fed by coaxial cables to the external parallel plates of the feedthrough. A central copper rod and an outer brass cylinder form a coaxial system which connects to the external parallel plates and which carries the current into the vacuum to the internal plates of the single turn coil of 22 nH inductance. The vacuum seals are provided by O-rings at the outside flange and by the concentric O-ring grooves in the epoxy insulation between the external parallel plates. The major portion of the insulation between the coaxial conductors is provided by a thickness of Mylar 0.015". The insulation at both ends where the coaxial geometry joins the parallel plates consists of vacuum-cast epoxy. The feedthrough is assembled by tightening the massive screws on top of the loadline which assures proper vacuum tightness by adequately compressing the two O-rings. This also provides the necessary holding force against the pressure caused by the magnetic field at the input plates. Subsequently, the complete feedthrough assembly is fastened against a porthole of the vacuum chamber in which the experiment is being conducted. The feedthrough constructed was 12" long and featured a measured inductance of 3 nH. It was tested statically up to 15 kv and in operation currents in excess of 0.4 MA were passed at 10 kv. During use this configuration already has been subjected to at least 3000 pulses under similar conditions without any vacuum leakage or voltage breakdown problems. The vacuum tightness of this seal was tested with a helium leak detector and the leakage rate was found to be below 10^{-8} cm^3/sec. During the initial operation of any new feedthrough inserted into a vacuum system some outgassing is noticeable upon application of the high current pulse; however, this effect subsides eventually after several shots. The effect is attributed to the mechanical shock and the transient heating of the residual gas between the two coaxial conductors. The present type of feedthrough has demonstrated dependable performance up to 0.4 MA which is not a limitation of the device but an energetic limitation of the capacitor bank used. It is reasonable to expect that geometries of the same or of somewhat larger diameters will be operable in the region of several MA. Since the azimuthal magnetic field B_θ goes like $1/2\pi R$, a judicious selection of a sufficiently large radius will allow to keep the enclosed magnetic field well below the critical field values and hence all deleterious effects of shocks and deformation can be virtually eliminated.

ACKNOWLEDGEMENTS

The authors express their appreciation to Mr. S. W. Lee and to Mr. R. G. Davis for their help in the work connected with this development.

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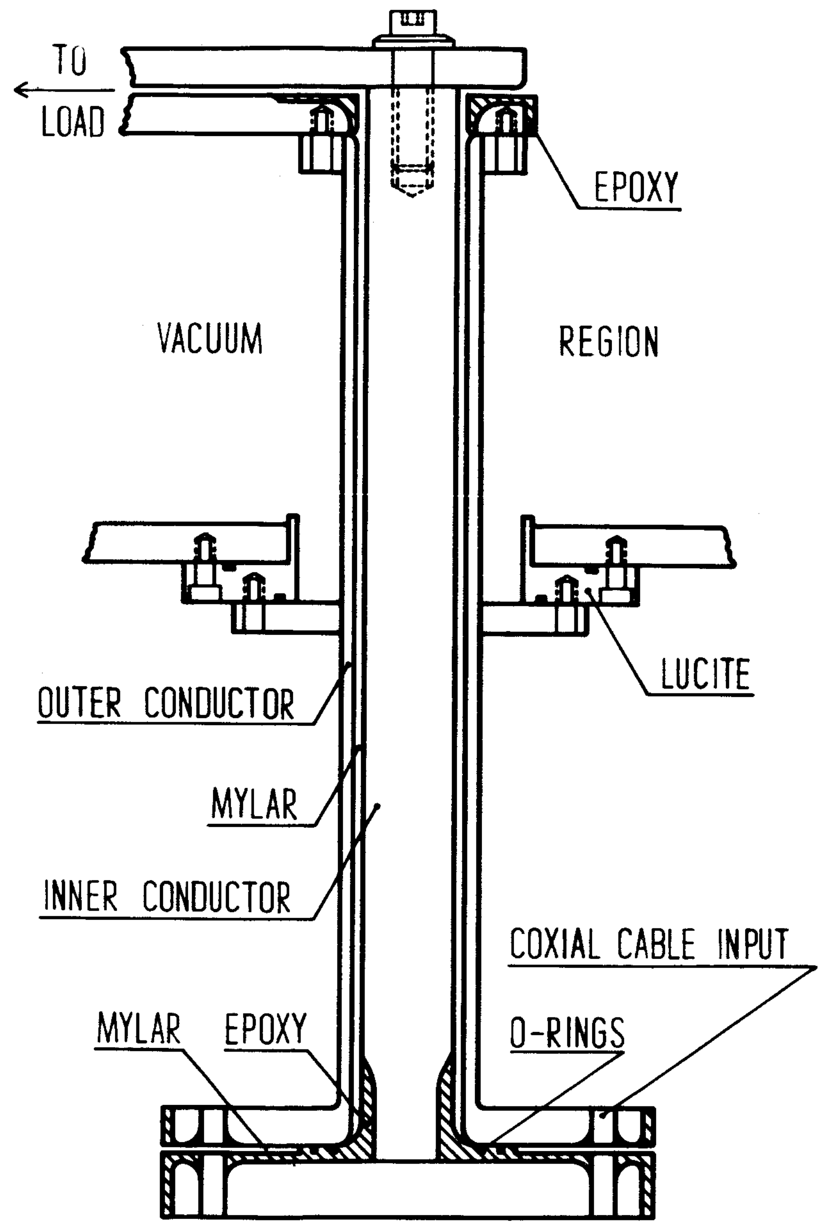
2) H. P. Furth, M. A. Levine, R. W. Waniek, Rev. of Scientific Instr. Vol. 28, 949, 1957.


TO
LOAD
EPOXY
VACUUM
REGION
LUCITE
OUTER CONDUCTOR
MYLAR
INNER CONDUCTOR
COXIAL CABLE INPUT
MYLAR
EPOXY
O-RINGS